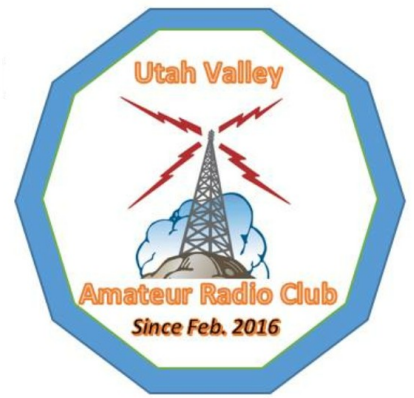


# Brass Tacks

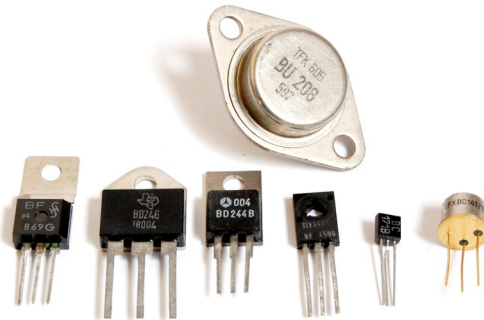
*An in-depth look at a radio-related topic*



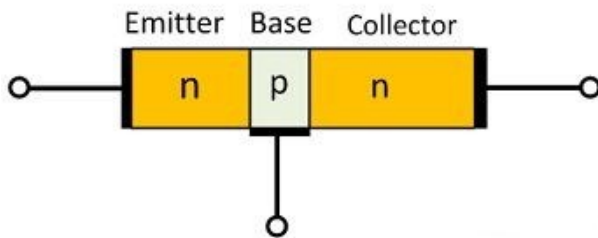
## How transistors work

The *transistor* seems to be a mysterious yet indispensable and ubiquitous (found everywhere) electronic component that invisibly performs magic on a circuit very rapidly. If you've ever wondered what transistors really are, or how they work, this might be your chance to get a little insight without having to go back to school. As a caveat, this article will make purists either squirm or smile, because in my attempt to keep the subject matter simple, I'm going to make some generalizations that will hopefully help you understand but not overwhelm you by distracting details of this complex little wonder.

*Solid state* is the term we use to distinguish between equipment that uses semiconductors instead of vacuum tubes. It's a kind of weird term, because both semiconductors and vacuum tubes are physically solid, not a gas or liquid, although the electron stream in tubes could be thought of as a type of gas or plasma of electrons. At any rate, we use the term solid state to describe transceivers, amplifiers, and other amateur radio equipment that use some semiconductor components rather than vacuum tubes to perform the same or similar functions.



A *semiconductor* device is a term that describes either a diode or a transistor. An *integrated circuit* is a semiconductor component that is made of many transistors, plus other components. Diodes and transistors are very similar in the way they fundamentally work, so let's focus on the transistor. Transistors can be either a bipolar-junction (BJT) or a field-effect (FET) type, and BJTs can be NPN or PNP, but this article will not distinguish between any of them.



Originally, transistors were intended to replace the bulky and energy-hogging vacuum tube, but ironically the first transistors were vacuum-sealed in glass tubes because of their delicate construction. A transistor is made of three pieces of a poorly-conducting material (either Silicon - Si, Germanium - Ge, or Gallium Arsenide - GaAs), one piece sandwiched in between the other two pieces. The middle piece is

lightly soaked in a kind of conductive poison, and the two outside pieces heavily soaked in another kind. (In reality, they're just one piece that's *doped* in two different ways, but I'll use the three-piece description to better illustrate how it works.)

This doping allows each piece to conduct electricity under specific situations, but not like a wire, which always conducts, and so we call them semiconductors. In general, a transistor is used either as an *amplifier* or a *switch*, with signal amplification being its original application, so let's start there. For simplicity, I'm going to refer to this three-piece device as a *threesome*, but understand that it merely represents a transistor with its guts revealed somewhat.

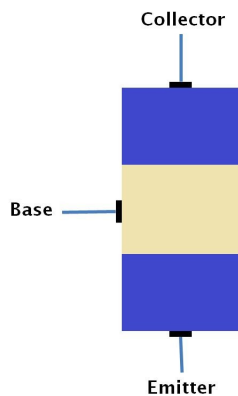
# Brass Tacks

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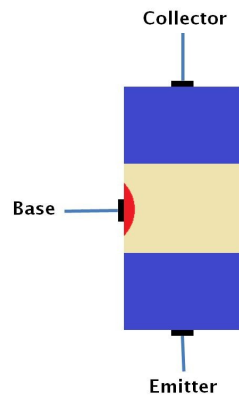


## Amplifier

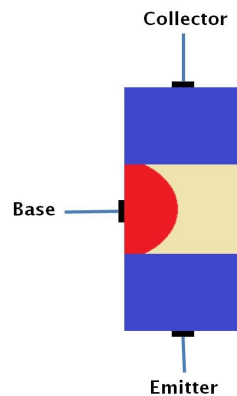
Let's imagine a simple, crude experiment. If you connect a battery across the two outside semiconductors of our threesome device, current will not flow through the three semiconductors, because the middle one is not conductive in this configuration (Figure 1). Now's when it gets tricky. If you apply a very small voltage to the middle (Base) piece (with respect to the outer piece connected to the negative battery terminal), something starts happening. Invisibly, a small region (in red) of the material in the middle piece becomes conductive, but the region isn't large enough to reach the outer pieces, and so no current flows just yet (Figure 2).



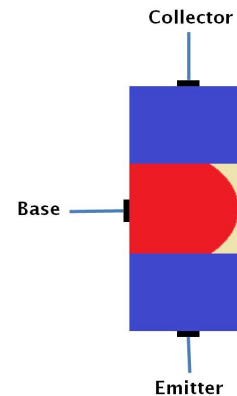
*Figure 1*



*Figure 2*



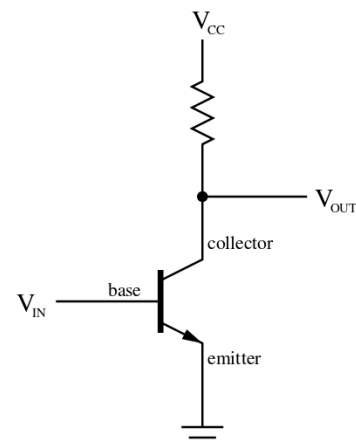
*Figure 3*



*Figure 4*

Ok, raise the Base voltage a little more, and the region grows just barely enough to touch both outside pieces, and suddenly current starts flowing through the threesome, from the positive terminal (Collector) to the negative one (Emitter, Figure 3). Raise the Base voltage even more, and even more current flows (Figure 4). It turns out that the current through this threesome is proportional to the voltage you apply to the Base. Furthermore, if you insert a resistor between the battery positive terminal and the Collector (Figure 5), you can measure the voltage across this resistor, which will reflect the change in current through the threesome, which also proportionally reflects the change in voltage applied to the Base.

In fact, if the battery voltage is large (think 3 to 5 volts) compared with the voltage you apply to the Base (think 30 to 50 millivolts), it's apparent that the voltage waveform measured across your resistor will be proportional to the voltage waveform you apply to the Base, only much larger. That's the definition of an *amplifier*. And this forms the basis on which a transistor is used in an actual amplifier circuit, which is fundamental to oscillators, detectors, frequency converters, and discrete radio and audio amplifiers.



*Figure 5*

# Brass Tacks

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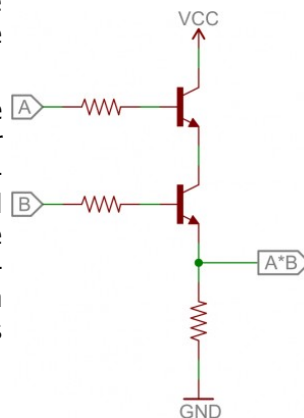
## Switch

Now that you know how a transistor can function as an amplifier, let's make two changes to our threesome device. First, let's move the resistor to the other end, between the threesome (Emitter) and the negative battery terminal. Since it's in series with the threesome, it shouldn't make any difference where we place the resistor, but we'll move it for experimental convenience. Next, instead of applying a low voltage to the Base (or *gate* on a FET), let's apply a much larger voltage, one large enough to completely *saturate* the middle piece with the conductive region.

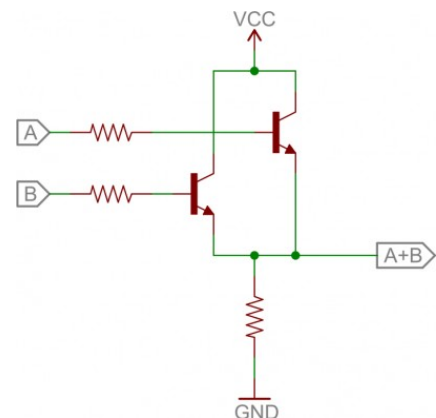
In this condition, the threesome becomes as conductive as it could get. Current rushes through the threesome, through the resistor, to the negative battery terminal, measuring close to the battery voltage across the resistor. Now, reduce the base voltage to near zero, and the resistor voltage goes to zero. This flip between saturation (conduction) and cut-off of the middle piece now acts like an *electronic switch*, and forms the basis for *logic gates*, fundamental to all computer circuitry.

Using this switch configuration, if you connect two of these threesomes in series, it's obvious that close to zero volts will appear across the resistor until both inputs (base voltages) are at full voltage. This is called a logical AND gate, because both input voltages must be at high ("1") voltage in order for the output to present a high voltage. And if you connect these two threesomes in parallel, it should be apparent that the voltage across the resistor will present a high voltage if *either* of the base voltages is at full voltage. This is called a logical OR gate, because either input voltage can be at a high voltage in order for the output to present a high voltage.

By the way, just how fast can these transistors switch, or in other words, how long does it take between the time voltage is applied to the Base, and for the middle section to reach saturation? In today's transistors, anywhere from billionths of a second to trillionths of a second.



*Transistor AND gate*



*Transistor OR gate*

## Integrated circuits

The advent of the electronic computer proved to be a remarkable milestone in human history. But dependence on numerous vacuum tubes, which failed at a rate of one to three per day in one of these computers, coupled with the enormous amount of energy required to function, prompted a lot of research into smaller, more reliable, and more energy-efficient computing devices. The invention of the transistor switch completely transformed computers, as well as other electronic devices, into smaller, more efficient, and faster devices with proven reliability many orders of magnitude greater.

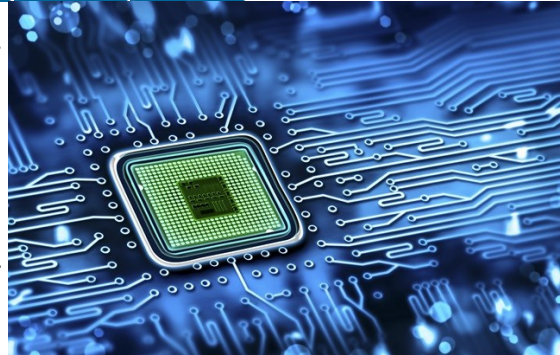


# Brass Tacks

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After a lot of experimentation, it was discovered that transistors can function in saturation / cutoff (on / off switch configuration) even when constructed at sizes much smaller than most discrete components, such as individual resistors, capacitors, and inductors. In applications where they're smaller than can be seen by the human eye, we call these tiny transistors *microelectronics*. And making them that small, we can build huge amounts of logic circuitry made of transistors working together in a package we call an *integrated circuit* or IC.



Today, everyday devices such as cell phones, laptops, GPS, complex medical monitors, and handheld ham radios are now possible because of the multitude of transistors built into microelectronic ICs. And while vacuum tubes were once purchased for \$1 to \$7 per tube, each transistor can cost under a billionth of a penny, and perform the same function for less than a trillionth the power. In the late 1980s Johnny Carson once joked that, if cars exhibited the same progress as computers, they would now cost a third of a cent, get 50 million miles a gallon, and fit on the head of a pin. Not sure people are laughing anymore, because things everywhere are progressing so rapidly, thanks to the microelectronic transistor.



And speaking of ham radio, newly manufactured rigs of all kinds, from handhelds to base stations, are made with ICs. Transistors have enabled us to embed very complex and fast digital signal processing (DSP) for filtering, digital conversion for ease of signal manipulation, and digital presentation of human controls. In fact many of today's ham radios are nothing less than computers with add-ons, so that much of the processing functions are performed by software or firmware installed in the rig, which we call *software-defined radio* (SDR).

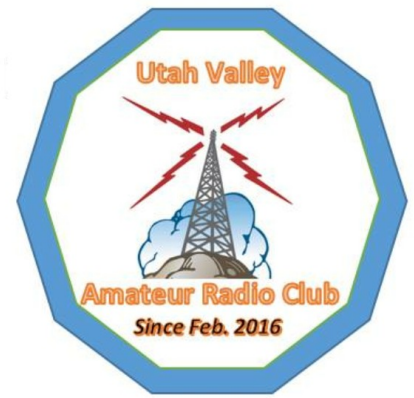
## The MOSFET

Many of today's computers and other high-tech devices have to rely on small-battery power, which means those many, tiny transistors can't afford to use much energy. For low-power



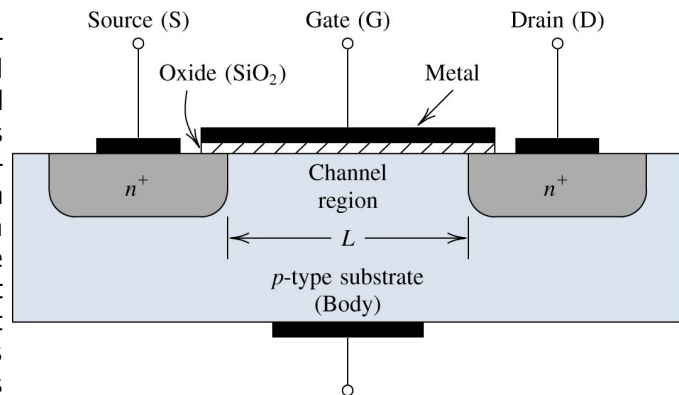
# Brass Tacks

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needs, the *MOSFET* (metal-oxide-semiconductor field-effect transistor) was developed to perform the same function as a regular transistor, but at much lower power consumption. The only real difference between a MOS transistor and a regular one (BJT or JFET) is its construction, but the benefits are enormous.

The wire to the Gate of the MOSFET transistor connects to a piece of metal (typically Aluminum), which is deposited on an oxide layer (usually  $\text{SiO}_2$ ), which is then deposited on a semiconductor substrate (usually Silicon), hence the term metal-oxide-semiconductor. Confusion about the meaning of MOS exists because the term often leads people to believe that some sort of metal oxide is involved, but no oxidized metal is involved in today's semiconductors. This construction lends itself to low-power operation because very little current actually passes through the transistor due to the insulating effect of the oxide layer. ( $\text{SiO}_2$  is the chemical formula for glass, by the way.)



*Metal-oxide-semiconductor construction*

There are other types of transistors, some with very specialized functions, but what I've tried to describe is the general workings of the most common types, to give you an idea of how a generic transistor works. Furthermore, because a transistor is built kind of like a pair of diodes that share the same Base, you can test the relative integrity of a transistor by measuring its diode effects between the Base and Collector and the Base and Emitter. But a transistor is more than a pair of diodes, so you can't really make a transistor with a couple of diodes, because they don't share a common substrate, which allows for the field effect that creates the conductive region.

## Summary and conclusion

A transistor is an electronic component with three terminals, one connected to each of three sections of a multi-way doped semiconductor, which becomes a good conductor if the middle section (base or gate) has a voltage applied to it. It can act as an amplifier because the conduction of the transistor reflects the varying voltage applied to the base. A transistor can also serve as a switch when the conduction is all the way on or off. Transistor switches form the basis for computer logic circuits, and when made very small, still function well as microelectronics in applications such as integrated circuits.

Because transistors have found their way in nearly every application in daily life, especially in devices that have saved countless lives, it's considered one of the greatest inventions of the 20th Century. What do you think will be among the greatest inventions of the 21st Century?

— Noji Ratzlaff, KNØJI ([kn0ji@arrl.net](mailto:kn0ji@arrl.net))